OPIMISATION OF EMPTY RAIL WAGON RE-DISTRIBUTION

R. P. Mutyavavire[1*] and K.Battle[2]
[1]Department of Industrial Engineering
University of Johannesburg, South Africa
rmutyavavire@uj.ac.za

[2]Faculty of Engineering and the Built Environment
University of Johannesburg, South Africa
kbattle@uj.ac.za

ABSTRACT

Rail freight network service design is characterized by asymmetrical demand by volume. The loaded wagon in-flow to a specific region is generally unequal to the out-flow from that region. Over time, an imbalance in wagon resource and capacity is realized in the network. The periodic re-distribution of empty wagons is necessary. Re-distribution is non-revenue earning and a cost. To minimize cost and improve efficiency, the empty wagon mileage should be optimized (minimized). Traditionally, operational planning was effected through reasoning and head knowledge of operating staff. The human element renders the resulting system behaviour inherently inconsistent and sub-optimal, particularly with increasing network size. A need arises for a management decision support system that consistently guarantees optimized aggregate empty mileage and associated costs. This paper formulates and applies a linear programming (LP) based mathematical model as a Decision Support System (DSS) to the empty wagon re-distribution management problem. Network capacity and resource constraints are considered. The model is applied to a medium sized African rail freight operator with encouraging results.

*Corresponding Author

1 INTRODUCTION

The Southern Africa regional economies are increasingly reliant upon export of primary commodities [4]. Freight transportation service arises from the spatial distribution of resources and customers, and is a key economic activity in this respect [5]. Freight transport consequently constitutes a significant cost element in the value chain for most products [6]. Transport and communication services are pre-requisites for economic development and global competitiveness and efficient economies seek to minimise total logistics costs [19].

The Rail freight mode of transport affords significant advantages to an economy over road freight particularly for bulk commodities. The advantages include among others, reduced carbon emissions, cost competitiveness, superior safety and reduced road congestion [7].

A rail freight transport system constitutes several resource classes namely wagons, locomotives, personnel, infrastructure, and management systems to name but the more significant [8]. The overall system operational efficiency is a function of the utilization efficiencies and productivity levels of these resources.

The wagon fleet constitutes approximately 40% of the total asset value of the average rail road operator, arguably the most significant resource class. It is estimated that the average wagon in a typical rail network moves 45% of its gross mileage empty [9]. Additional waste in the form of wagon dwell time, load/unload time, maintenance imperatives, and operational inefficiencies further reduces fleet utilization. Key efficiency metrics applicable to the transport industry include, route efficiency, utilisation efficiency (empty mileage), and load factor [10].

Rail network operations are characterized by asymmetrical demand by volume. The loaded wagon inflow to a specific region is unequal to the loaded outflow from that region. Consequently, over time, an imbalance in empty wagon resource and capacity manifests in the network. This imbalance necessitates the periodic re-distribution of empty wagons from surplus points to economically convenient loading points [11].

Empty wagon re-distribution is non-revenue earning. The aggregate empty wagon mileage should be optimized (minimized) in order to improve operational efficiency [20]. Improved resource utilization contributes towards optimal fleet sizing, positively impacting return on capital, maintenance and ownership costs.

Sayarashad et al. [1] formulated and provided a solution procedure for optimal fleet sizing and empty wagon allocation assuming deterministic transit times and demand. The reduction of empty movements in transportation reduces logistics costs, improves economic performance and decreases operational problems and environmental impact [3]. Empty repositioning management can benefit from advances in information and communication systems and their integration with optimization modelling [3].

The case of a southern Africa based freight rail operator is considered, with special emphasis on empty wagon re-distribution management. For the operator under study, tactical day-to-day planning of empty wagon re-distribution is largely effected by a centralized group of operational staff, employing collective reasoning and head knowledge. The decisions arising are subject to human proficiency levels and cyclical human behavioural patterns. The hypothesis held is that the behaviour of the operational system arising is inherently inconsistent and sub-optimal, particularly with increasing network size and traffic volumes. The critical need for a management DSS to complement human effort and guarantee optimized tactical planning arises.

Complex resource layering arrangements precede any train movement. The resources include locomotives, operating crew, loaded wagons and infrastructure, to mention the more significant ones. Availability and reliability of each of these resources constitute a significant constraint in empty wagon distribution.

Leddon [12] considered the empty rail wagon allocation problem, applying the transportation model as solution methodology, using estimated wagon supply and demand as well as time invariant events. In spite of the assumptions, the model provided promising results.

Turnquist [13] presented more realistic integer flow formulations again assuming deterministic wagon demand and flow patterns, yielding improved operating results. Powel [14] added realism to the formulations and developed dynamic stochastic models for the empty wagon distribution (EWD) problem, accommodating the stochastic nature of demand and flow patterns. Powel [8] notes that the demand for services in freight rail transport over time and space is typically random. Arvidsson [10] emphasizes the need for expeditious servicing of demand to minimize opportunity costs in freight business.

Beurrier [15] integrates mathematical optimization modelling and expert systems in order to accommodate business strategic objectives. Zhang [17] presents an ICS based intelligent DSS for EWD management and Giannetoni [7] incorporates cloud computing and GPS technologies in an ICS based optimization model with promising results.

Ferreira [16] notes that the practical implementation of EWD by rail operators remains unsatisfactory. Powel [18] suggests that the unsatisfactory implementation levels is because much current research focuses upon myopic heuristics, with minimal realism. He further notes that solutions to railway optimization models are complex and this has resulted in over simplification of most formulations, in turn imposing limitations on practical relevance and implementation aspects of the models.

This research effort aims to determine the impact of LP based mathematical modelling to the empty rail wagon re-distribution problem in a medium sized African freight rail operator in order to contribute towards development of effective and applicable DSS in the freight rail industry on the African continent. The model emphasis is on realism and practicality.

2   PROBLEM DESCRIPTION

Rail freight networks are typically unbalanced across space and time, characterized by increasing wagon inventories at some nodes and deficit levels at some. The imbalance necessitates periodic empty wagon re-distribution. The need arises for a tactical day-to-day strategy for the re-positioning of the empties, with the objective to minimize aggregate empty mileage and improve operational efficiency. For the case under study:

- Wagon re-positioning day-to-day tactical planning is manual, time consuming and characterized by priority conflicts.
- The rail operator consistently fails to achieve planned empty wagon placement targets.
- Resource layering constraints are not systematically integrated into the tactical planning and execution systems.
- The operator under study applies a 24 hour planning and execution window.
- Wagon supply lags demand.
- The problem is to determine how many empty wagons to send empty from node i to node j.

3   METHODOLOGY

In order to develop a feasible management DSS applicable to the Empty wagon distribution (EWD) for the rail operator under study, the methodology adopted integrates statistical analysis, mathematical programming and ICS. The main steps of the methodology are as follows:

(i) The daily empty wagon demand and supply statistics for a 90 day sample period covering july – September, were collated from operator record sheets. The 10 most significant hubs (nodes) by demand/supply were identified. The rail network was simplified to reflect only the ten nodes.

(ii) The aggregate empty mileage to satisfy the empty wagon demands for the simplified network using the baseline operating model was determined for the sample period.

(iii) An LP based mathematical optimization model, incorporating constraints arising from resource layering imperatives was formulated. The baseline demand and supply variables for the 90 day simulation period were applied as the input variables.

(iv) The response variable, the aggregate empty mileage (cost), of the baseline model was evaluated relative to the response variable output of the simulated mathematical model.

(v) The mathprog software was used.

4   SYSTEM MODELLING AND FORMULATION

In line with the above stated current work objectives, we consider the problem of managing the re-distribution of railway empty wagons over space and time in an environment where capacity lags demand. In such a network, a node represents a city (wagon demand/ generation point) and an arc represents the link between any pair of nodes. The primary objective is to minimise aggregate empty wagon distance hence total transportation cost.

It is assumed planned wagon re-positioning is achieved within 24hrs and demand not satisfied in that period is lost. The succeeding planning window is considered independently.

4.1   Nodal allocation

When capacity lags demand, it is necessary to put in place a sustainable allocation system to allocate the limited resources. Pertinent determinants of nodal allocations include:

Nodal demand   = r_i

Nodal empties generation   = g_i

Global demand   = r_g

Global supply   = S_g

The global supply ratio, d_{ni} = $\dfrac{s_g}{d_g}$

Periodic nodal allocations   = A_i

=   f(r_i, d_{ni})

= $d_{ni} * r_i$

$A_i,$ guarantees equitable resource allocation when supply lags demand.

Wagon surplus at node $N_{i,}$ = S_i

S_i = $g_{i \ -\ (r_i \ * \ d_{ni})}$

4.2 Transportation model

4.2.1 Notations and formulation

Having determined the nodal empty wagon allocations per time window, the next problem is to determine optimal distribution pattern. To formulate this problem the following assumptions (in line with current operational norms) are made: -

- There is only one type of capacity. Any unit of capacity is compatible with any demand
- Shipments from one terminal to another are transported directly. Intermediate steps are not possible.
- Travel times are equal to one time period (24hrs).
- Shipment costs are independent of direction on the same arc.
- Wagon demand and transit times are assumed deterministic

The following decision variables are defined:

N_i = Wagon supply node

N_j = wagon demand/ destination node

X_{ij} = number of empty wagon from node *i* destined for node *j*

d_{ij} = kilometre distance between nodes *i* and *j*

C_w = incurred cost per wagon per unit distance (km) traversed

C_{st} = inventory costs per wagon at node *j*

= $C_{w^*} d_{ij}$

C_m = marketing cost

C_O = overheads costs

C_r = Maintenance and repair cost

g_i = empty wagon generation at node i

r_i = empty wagon demand in node i

l_t = long haul locomotive availability (numbers) in time period t

C_{rt} = Train operating crew availability (numbers) in period t

Z = is the set of nodes/terminals in the network

A_i = Nodal empty wagon allocation as determined by allocation formula

S_i = wagon surplus at node N$_i$

It is further assumed the cost per unit distance of each wagon is constant irrespective of load status.

The mathematical formulation of the empty wagon fleet management problem as given by:

Minimize,

$$\Box = \sum_{ij \in N} X_{ij}\, d_{ij} C_w + \sum_{j \in N} C_{st} \left(g_i - r_i - X_{ij} \right) + C_o + C_i + C_m$$

Where, $C_o + C_i + C_m,$ are constants,

The function, $\sum_{j \in N} C_{st} \left(g_i - r_i - X_{ij} \right)$

Constitute wagon storage costs i.e marshalling yard operational costs. For computational ease, yard operational costs are readily absorbable into the general transportation costs.

The final simplified formulation,

Minimise,

$$Z = \sum_{ij \in N} X_{ij}\, d_{ij} C_{tw}$$

Where:

C_{tw} = aggregated unit wagon shipment cost.

4.3 Constraints

In the system under study, three critical constraints have been identified. These are, train crew, locomotives and infrastructure.

4.3.1 Train crew constraints

The availability of operating train crew presents a constraint on system's ability to effect planned wagon distribution. The respective inequality constraint has been derived as:

$$0.03\sum X_{ij} \;\geq\; \frac{1}{d_P} * \left(1 + U_s \right) \sum \frac{S_i}{33}$$

4.3.2 Infrastructure constraints

The wagon handling capacity per arc, in unit time, is a complex function of the under listed variables:

a) Temporary bottlenecks - arising from accidents and recovery work, environmental and weather elements etc.
b) Infrastructure condition - a function of maintenance and general upkeep of signalling and permanent way facilities
c) Design limitations

For simulation purposes, surveys backed by the minimal statistical data available, were employed to determine current realisable wagon clearance capacity for each arc. These arc

clearance capacities were then adopted as the respective arc constraints. Table 1 below illustrates these constraints.

Table 1:Arc wagon clearance Capacity per day

ARC	DESIGN CAPACITY	CURRENT REALISABLE
X_{910}	14 Trains	4
	462 Wagons	132
X_{89}	19Trains	6
	627 wagons	198
X_{78}	26 trains	8
	858 wagons	264
X_{27}	21 trains	4
	693 wagons	132
X_{47}	19 trains	4
	627 wagons	132
X_{46}	14 trains	2
	462 wagons	66
X_{45}	17 trains	2
	561 wagons	66
X_{34}	16 trains	3
	528 wagons	99
X_{21}	19 trains	5
	627 wagons	165
X_{211}	12 trains	1
	396 wagons	33

4.3.3 Motive power constraints

Motive power (locomotives) is necessary for hauling trains. The defining inequality constraint for locomotives is derived:

$0.05 \sum X_i \geq 512$, based on current locomotive availability and reliability indicators.

Locomotive failures at origin nodes result in train cancellations, whilst failure in transit causes premature train termination. In both cases, additional motive power capacity is necessary to achieve planned wagon redistribution target.

4.4 Generalised formulation

From section 4.2, we present the generalised formulation:

Minimise,

$$Z = \sum_{ij \in N} X_{ij}\, d_{ij} C_{tw}$$

Subject to constraints:

$$\sum_{ij \in N} X_{ij} \geq 1.67 \sum_{i \in N} S_i$$

$$\sum X_{ij} \geq \frac{1}{d_P} * (1 + U_s) \sum S_i * \frac{1}{0.03}$$

$$X_{9,10} \leq 11880$$

$$X_{8,9} \leq 17820$$

$$X_{7,8} \leq 23760$$

$$X_{2,7} \leq 11880$$

$$X_{4,7} \leq 11880$$

$$X_{4,6} \leq 5940$$

$$X_{4,5} \leq 5940$$

$$X_{3,4} \leq 8910$$

$$X_{2,1} \leq 14850$$

$$X_{2,11} \leq 2970$$

5 DATA PREPARATION

Considering the 90 day simulation period, aggregate demand per node is tabulated below:

Table 2: Aggregate Nodal Demand

NODE	DEMAND	SUPPLY	S_i	g_i
1	8603	7133	-6108	0
2	12109	10000	3402	12000
3	0	0	0	0
4	940	632	-688	0
5	4901	2033	-3480	0
6	2643	2438	1624	3500
7	6500	3187	1385	6000
8	14353	9760	3710	13900
9	2198	1696	136	1679
10	0	0	0	0
Total	52247	37079	0	37079

Global satisfaction ratio, d_{ni} = $\dfrac{S_g}{d_g}$

= $\dfrac{37079}{52247}$

= 71%

Due to the absence of reliable and accurate data on nodal generations, most g_i values are estimates based on surveys and scanty data available.

6 NUMERICAL RESULTS AND DISCUSSION

An attempt is made to establish in numerical terms relative performance of current against proposed operational models. Two measures of performance are put to use:

a) Redistribution cost
b) Empty wagon mileage index

From the operator's database, wagon conveyance costs per unit distance, has been calculated to be:

= $ 65,036 per /km

Aggregate empty wagon mileage (for 90 day simulation period)

= 11065000km

Total distribution costs incurred   =   11065000 * 65,036

$\qquad$ TC$_1$ = $719623340

The baseline supply and demand input variables as shown in table 2, were applied to the model formulated in section 4.4. The Mathprog optimisation software was employed to solve the problem.

The response variable (aggregate empty wagon mileage) output at 71% demand satisfaction level:

$\qquad\qquad$ =   5 202 263.5km

The total re-distribution costs at 71% demand satisfaction level:

$\qquad$ TC$_2$ = $338 334 407

Direct costs savings: =   TC$_1$ -   TC$_2$

$\qquad\qquad$ = $ 381288933

Percentage saving   = $\dfrac{381288933}{719623340}$

$\qquad\qquad$ =   53%

7   CONCLUSION

The linear programming based empty wagon re-distribution model shows encouraging results. Relative to current operational systems with all other operational parameters fixed, a 53% reduction in empty wagon mileage and associated costs is recorded

The hypothesis is proved correct, the current operations model is sub optimal. Mathematical programming can be integrated into management DSS for the EWD problem in the context of African railroad operations with considerable success.

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